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13. ABSTRACT *(Maximum 200 words)*

This project resulted in the development of several novel optical fiber lasers designed to generate short pulses for optical communication networks and for optical signal processing. The concept of using asynchronous modulation for stable soliton generation was developed and extended successfully to optical memory loops. Laser designs for reduced sensitivity to environmental perturbations were investigated and important properties of dispersion management revealed. A compact geometry was demonstrated using a doped, planar waveguide amplifier and the shortest soliton pulses to-date, from a fiber source were achieved.

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FINAL TECHNICAL REPORT

AASERT Grant No. F49620-95-1-0435

"Asynchronous Modelocking of fiber Lasers"

Project Period: August 1, 1995 – July 31, 1998

Principal Investigator: Erich P. Ippen

Executive Summary

This project resulted in the development of several novel optical fiber lasers designed to generate short pulses for optical communication networks and for optical signal processing. The concept of using asynchronous modulation for stable soliton generation was developed and extended successfully to optical memory loops. Laser designs for reduced sensitivity to environmental perturbations were investigated and important properties of dispersion management revealed. A compact geometry was demonstrated using a doped, planar waveguide amplifier and the shortest soliton pulses to-date, from a fiber source were achieved.

Background

A theoretical paper published in 1992 proposed that a fiber loop with gain, filtering, and an amplitude modulator could indefinitely store a bit pattern of ones and zeros. In 1994, we demonstrated the storage ring principle by storing 66 bits at 1 Gbit/sec. Subsequent refinements have upgraded the performance to 3.8 kbit packet stored at 50 Gbit/sec. In each of these experiments, standard non-polarization maintaining fiber is used in a ring along with polarization controllers. Such a configuration allows for additional stabilization and noise cleanup via Polarization Additive Pulse Mode-Locking (P-APM).

Increasing the long-term stability of storage rings could be accomplished by using polarization maintaining (PM) fiber which forces the signal along a single polarization. However, by propagating single polarization in PM fiber, the benefits of P-APM are necessarily lost. To investigate how the elimination of P-APM would affect the performance of storage rings, we constructed a ring using all PM fiber. Results from our experimental work indicate that, despite the absence of P-APM, a 1 kb pattern at 5 Gbit/sec can be successfully stored. This is an encouraging result as it demonstrates the possible implementation of storage rings in PM fiber. In addition, two supplemental results emerged from this work.

First, by having PM fiber in the loop, laboratory results could be directly compared with theory. The presence of P-APM in previous experiments did not allow for such a comparison. In our original paper, long-term storage was theoretically found only within a window of system parameters. Experimental investigation of the predicted stable storage window gave a surprisingly close agreement with theory, thereby confirming our analytic treatment.

A second, additional result of our work concerns the width of pulses produced by the storage ring. If the storage ring is given enough gain, all the time slots will fill with pulses and the storage ring becomes a normal actively mode-locked fiber laser. Measurement of the pulses' width within our ring indicated they were approximately 600 fs wide, significantly shorter than predicted by standard active mode-locking theory. Nonlinear (soliton) effects are responsible for the pulse width reduction, a technique which has long been proposed as pulse width reduction mechanism in actively mode-locked fiber lasers. Our results appear to be the first observation conclusively demonstrating the possibility of this method to shorten pulses in actively mode-locked fiber lasers.

One of the drawbacks of using P-APM is the sensitivity of loop operation to environmental changes in temperature which affect the net birefringence in the loop and hence the polarization bias and stability. Thus it becomes important to investigate methods for maintaining pulse pattern stability in a loop constructed of polarization preserving fiber. A promising approach previously demonstrated by graduate student Chris Doerr is that of asynchronous modelocking. In this approach a phase modulator is driven at a frequency slightly detuned from that of the desired cavity harmonic. The solitons in the loop are able to combat the this sliding phase modulation by self-phase modulation but low level signals (the zeros) are frequency shifted and can be suppressed by spectral filtering.

The goal of the following research was to demonstrate an asynchronous optical memory, to further investigate methods for improving stability against environmental changes and to investigate possibilities for making fiber laser loops more compact.

<u>References</u>

H.A. Haus and A. Mecozzi, "Long-Term Storage of a Bit Stream of Solitons", Opt. Lett. 17, 1500 (1992).

C.R. Doerr, W.S. Wong, H.A. Haus, and E.P. Ippen, "Additive-Pulse Mode Locking/Limiting Storage Ring," Opt. Lett. 19, 1747 (1994).

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J.D. Moores, W.S. Wong, and K.L. Hall, "50 Gb/s Optical Pulse Storage RIng Using Novel Rational-Harmonic Modulation," Opt. Lett. 20, 2547 (1995).

Asynchronous phase-modulated optical fiber ring buffer

Continuing our work on asynchronous fiber lasers, we have applied the principle to an optical fiber ring buffer. The asynchronous mode of operation offers several practical advantages over synchronous operation including tolerances of drifts in cavity length and loaded packet characteristics as well as possible elimination of clock recovery on incoming packets. We demonstrated successful loading, storage, and unloading of 5 Gbit/sec packets from an asynchronous phase-modulated optical fiber ring buffer. In addition, relaxation oscillations, which have affected the storage time of previous high-speed optical ring buffers, are nearly eliminated with a CW holding beam and significantly enhanced storage times of least 157 • s (1600 circulations) were obtained. Limitations with our diagnostic equipment prevented us from observing storage beyond this limit.

Publications

D.J. Jones, H.A. Haus and E.P. Ippen, "Subpicosecond Solitons in an Actively Mode-Locked Fiber Laser," Optics Lett. 21, pp. 1818-1820, 1996.

D.J. Jones, K.L. Hall, H.A. Haus and E.P. Ippen, "Asynchronous Phase-Modulated Optical Fiber-Ring Buffer," Optics Lett. 23, pp. 177-179, 1998.

Environmentally stretched-pulse fiber laser

Previous versions of our stretched-pulse fiber lasers have been passively mode-locked in a self-starting ring cavity with non-Polarization Maintaining (non-PM) fiber. Such a configuration is sensitive to mechanical and temperature variations which may affect the laser's environmental stability. As a step towards obtaining high powers and broader spectra with a laser diode pump, we developed an alternate, environmentally stable cavity design. This laser is able to generate nano-joule pulses with 50 nm of spectrum that are compressible to sub-100 fs. Perhaps most significantly, this stretched-pulse laser requires 980-nm diode-pumping levels of only 200 mW and it represents the first stretched-pulse fiber laser which can be pumped by conventional laser diodes. Presently we are working with Clark-MXR to develop this version of the stretched-pulse laser into a commercial product.

Publication

D.J. Jones, L.E. Nelson, H.A. Haus and E.P. Ippen, "Diode-Pumped Environmentally Stable Stretched-Pulse Fiber Laser," IEEE J. Quant. Electron., 3, pp. 1076-1079, 1997.

Short cavity soliton source based on an Er-Yb waveguide amplifier

Due to limited dopant concentrations in erbium-doped fiber, nearly all previous fiber lasers mode-locked by polarization additive pulse mode-locking (P-APM) have cavity lengths of 4-5 meters long. In this project we investigated a passively mode-locked soliton ring fiber laser that used a 4.5 cm Er-Yb co-doped waveguide amplifier as the gain element. Integrated optical glass waveguides can be doped directly with erbium and ytterbium rare earths to produce optical amplifiers for 1.55 μm that are much shorter than those comprised of fiber. They also offer the possibility of on-chip fabrication of other components such as couplers and gratings. The short cavity that we demonstrated successfully (even with an added length of 1.3 m of fiber) simultaneously reduced three parasitic effects that have limited the performance of soliton fiber lasers: multi-pulsing behavior, resonant sideband formation and saturation of the P-APM mechanism. These improvements enabled generation of 116 fs solitons with a pulse energy of 160 pJ at a fundamental repetition rate of 130 MHz.

<u>Publication</u>

D.J. Jones, S. Namiki, D. Barbier, E.P. Ippen and H.A. Haus, "116-fs Soliton Source Based on an Er-Yb Codoped Waveguide Amplifier," IEEE Photon. Tech. Lett. 10, May 1998.

Resonant sideband generation in stretched-pulse fiber lasers

In previous investigations of stretched-pulse fiber lasers there was a notable absence of the resonant sidebands so prevalent in soliton lasers. In careful recent studies we have observed such sidebands in a stretched-pulse laser, and have demonstrated that they occur even when the net dispersion in the laser is normal. An interesting feature of this regime is the appearance of m=0 sidebands (i.e. phase matching resonances that are independent of the cavity periodicity. By varying the net dispersion of our laser we investigated sideband position as a function of dispersion and pulsewidth and shown correspondence with both simple analytical theory and simulation. The results should be of consequence to some dispersion-managed transmission systems as well.

<u>Publications</u>

D.J. Jones, H.A. Haus, L.E. Nelson and E.P. Ippen, "Stretched-Pulse Generation and Propagation", IEICE Trans. Electron. E81-C, pp. 180-188, 1998.

D. J. Jones, Y. Chen, H.A. Haus and E. P. Ippen, "Resonant Sideband generation in stretched-pulse fiber lasers," Opt. Lett. 23, pp. 1535-1537, 1998

PhD Thesis

This AASERT grant supported the research of David Jones who subsequently completed his PhD with a thesis entitled "Generation and Storage of Ultrashort Pulses Using Optical Fiber Devices" in November 1998. He is presently employed as a NIST Postdoctoral Fellow at JILA, University of Colorado.

List of Publications Acknowledging Grant No. F49620-95-1-0435

D.J. Jones, H.A. Haus and E.P. Ippen, "Subpicosecond Solitons in an Actively Mode-Locked Fiber Laser," Optics Lett. 21, pp.1818-1820, 1996.

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